EXPERIMENTAL RESEARCHES ON THE REPULSION RESULTING FROM RADIATION[1]

II.

HAVING completed the experimental investigation of the amount of repulsion produced by radiation on disks of various kinds, and coated with different substances, I turned my attention to the amount of repulsion produced when polarised light is allowed to fall on a plate of tourmaline suspended in vacuo in a torsion balance. It was originally thought that a slice of tourmaline, being black to a ray of light polarised in one plane, and white to a ray polarised in the other plane, would be repelled when the incident light was quenched by it, and not affected when the incident light passed through it. Experiments, however, prove that this action does not exist in any

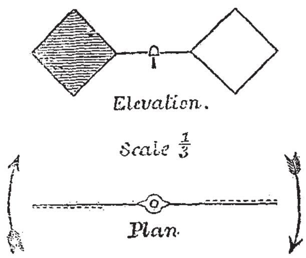

FIG. 4.

appreciable degree, the repulsion resulting from radiation being almost entirely a surface action, whilst the action of a tourmaline on a ray of polarised light is one in which thickness is necessary.

I next examined the effect of shape in influencing the amount and direction of repulsion. These experiments were for the most part tried with the apparatus shown in Fig. 3 (p. 513, part I.). Through the open top access can readily be obtained, and disks, plates, &c., can be quickly tested by being fixed to the extremities of a pair of aluminium arms, with a glass cap in the centre, rotating on the needle-point. Plates, 12 millims. square, cut from thin aluminium foil, were mounted diamond-wise on arms, and supported on the needle-point inside the bulb. The plates were lampblacked on sides facing

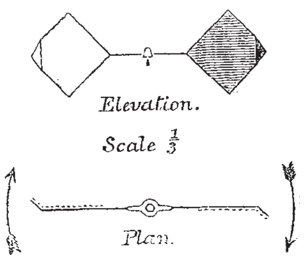

FIG. 5.

opposite ways, and the apparatus was well exhausted. The vanes behaved like an ordinary metal radiometer in respect to light and radiant heat. Fig. 4 shows the elevation and plan of the fly, the dotted side representing the one which was lampblacked. The arrows show the direction of positive rotation when exposed to the light of a standard candle 3·5 inches off. The outer corners of the aluminium plates were now turned up at an angle of 45°, 4 millims. of the two sides being turned up, leaving 8 millims. flat, as shown in Fig. 5. They were lampblacked on the inside, as shown in the figure by dots. A lighted candle 3·5 inches off caused very slow and feeble positive rotation. On shading the light from the black side, the bright side was repelled, causing positive rotation; and on shading the light from the bright side the black was repelled, causing negative rotation.[2] The positive repulsion was, however, rather stronger than the negative repulsion, so that, when both sides were illuminated, the force was only that due to the difference of these repulsions.

A hot glass shade is a convenient means of heating the bulb, by immersing it in a hot-air bath, without the liability of introducing action of rays other than those emitted by hot glass. On inverting a hot glass shade over the bulb in the above experiment, negative rotation was produced which changed to positive on cooling. Both these rotations were stronger than that given by the candle. The experiment was varied (1) by 6 millims. of the sides being turned up instead of 4; (2) by folding the plates across the vertical diagonal and then across their horizontal diagonal; (3) by attaching flat

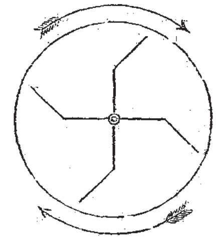

FIG. 6.

plates to the arms at an angle of 45°, blacking them on the insides away from the bulb, and repeating the experiment with plates blacked on the outsides. The results obtained show that when flat plates are taken blacked on alternate sides, the rotation is normal or positive, *i.e.*, the black side is repelled. When the outer corners of each plate is turned up so as to keep the blacked surface on the concave side, the positive rotation is either diminished, stopped, or converted into negative rotation, according to the amount of surface of the plate which has been turned up. The favourable presentation of the surface of the vanes to the inside of the bulb has more influence on the movement than has the colour of the surface. Radiometers constructed with silver flake vanes set at an angle

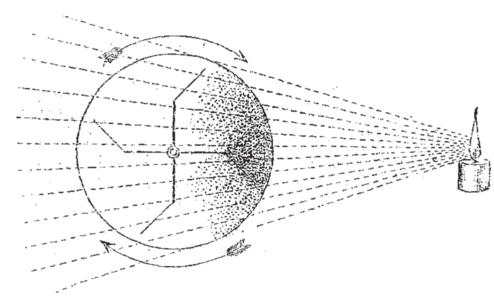

FIG. 7.

of 45° and blacked on the outside prove the most sensitive for light hitherto constructed.

I now endeavoured to clear up many anomalous results which had attended the application of heat either by hot shades or by hot water to radiometers. There was an antagonistic action between the effect of shape and that of colour of surface, the two actions sometimes acting together and sometimes in opposition.

Five radiometers were made exactly alike in size of bulb, shape of vanes, and degree of exhaustion, only differing in the material of which the vanes were composed. No. 1 was made of mica, 0·003 inch in thickness; No. 2, of mica, 0·0005 inch in thickness; No. 3, of pith,

[1] Continued from p. 514.

[2] I call the rotation *positive* when the black or driving side is repelled, and *negative* when the side which under ordinary circumstances would be the driving side, moves towards the light.

0·05 inch in thickness; No. 4, of aluminium, 0·002 inch in thickness. These four radiometers were plain on each side, no lampblack being applied. Their appearance is shown in Fig. 6. No. 5 was made of aluminium, identical with No. 4, but the vanes were lampblacked on each side instead of being bright. Had the vanes pointed radially there could have been no tendency for any one of the flies to move either way, but being inclined, the normal movement, on exposure to radiation, should be in the direction of the arrows—a direction which I called the *positive* direction.

In Fig. 7 the candle is represented shining on the bulb of the mica-vaned radiometer. The rays of light pass through the first wall without action. They then meet the mica, and that also being transparent, the rays pass through it likewise, and then escape through the opposite side of the bulb as is shown by dotted lines, without absorption and consequently without doing work. But in addition to light the candle is radiating ultra-red dark heat-rays, which in great measure are arrested by the glass, and raise its temperature. The inner surface of the bulb then becomes the surface on which molecular pressure is generated, which may be called the *driving* surface; this is shown by the shading next the candle. This molecular disturbance presses on the mica-vane which is in front of it, and drives it round in the direction of the arrows as if it were subjected to a bombardment of small shot. The vanes, in fact, may be said to be blown round by what may be likened to a wind, which however is not *molar* but *molecular*, inasmuch as there is no wind

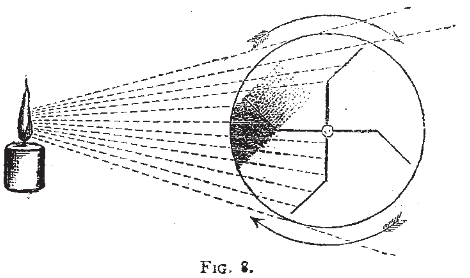

FIG. 8.

in the sense of an actual transference of gas from one part of the bulb to the other.

In Fig. 8 I have endeavoured to represent part of the action which takes place when the candle shines on the aluminium radiometer. The light passing through the bulb falls on the aluminium plate, and raising its temperature, causes pressure to be exerted on all sides. The molecules rebounding from the face next the glass, cause increased molecular pressure on that side, and produce movement in the direction of the arrows, or positive rotation. As each vane passes the candle it takes up heat, and acquires extra *driving* energy. As it swings round, the opposite side of the glass acts as a *cooler*, and by the time the vane has completed the circle, and has radiated away some of its extra heat, it is ready to recommence the cycle of transformation—light, heat, molecular pressure, motion.

Unlike mica, which generates very little pressure on its surface, the aluminium fly carries sufficient driving power to enable it easily to pass the dead centre opposite the candle. Therefore, as soon as the candle has shown on the aluminium radiometer long enough to warm the vanes a little, rotation readily continues.

The action of the pith radiometer is similar to the aluminium, except that the dissipation of pressure from the back surface of the pith will be almost *nil*. The pith, moreover, being sensitive to the heat-rays, and being a non-conductor, moves quicker than the aluminium, which requires time to get warm throughout.

The agreement between theory and observation, so far, seemed exact. I now tried numerous experiments with dark heat applied in various ways to these five radiometers. The results I obtained led me to think that the kind of dark heat might vary in refrangibility according to its source, and that the rays from hot water, hot glass, and hot metal, might affect the materials composing the vanes in a different manner, and being absorbed by one body and transmitted by another, might cause the positive or negative rotation which I obtained. I immersed the five radiometers in boiling water, and after cooling again immersed them in water only a few degrees above the temperature of the room; the results were similar to those I had previously obtained with water of 70° C. The radiometers were covered successively with hot shades of English, French, and German glass of different thicknesses, and at different degrees of temperature. The bulbs were also heated with a gas or spirit flame, but no uniform results were obtained.

A funnel was then heated in boiling water, and allowed to rest on the five radiometers in succession. They all moved in the *positive* direction, except the bright aluminium radiometer, which remained stationary. When the funnel was removed, the two aluminium and the thick mica radiometers rotated positively till they were cold. The funnel was allowed to cool. It was then inverted over a radiometer, and steam was passed through for a second or two. The same experiment was repeated with each radiometer. The results were now equally uniform with those of the last experiment, but the rotation was

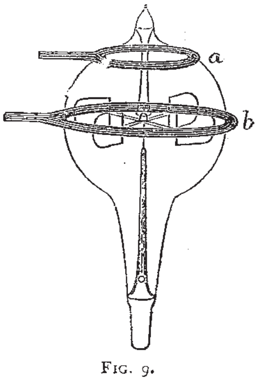

FIG. 9.

negative, the bright aluminium fly moving the best o all, and the pith fly the least.

I repeated the experiment with a thick brass ring, the internal diameter of which was about half that of the bulb (Fig. 9, *a*) and then with another brass ring a little larger in diameter than the bulb, *b*, Fig. 9. These rings were each heated to about 400°. With the first the rotation was *negative*, while in the second all the flies revolved in the *positive* direction. The two brass rings were made red hot, and held in position till the flies were in rapid movement, when the rings were removed and the hot part of the bulb dipped into cold water, so as to chill the glass quickly, and still keep the fly warm. These experiments proved that when heat is applied round an equatorial ring of the bulbs the rotation is always in the positive direction. The hot ring of glass generates molecular disturbance, which presses towards the centre and strikes the sloping vanes, driving them round as if the wind were blowing on them. In Fig. 10 I have tried to represent this action. The positive movement is independent of the material of which the fly is made, and is only slightly increased or diminished according to the conducting power of the fly for heat. The lighter the weight of the fly to be driven round, the easier it moves, and the heavier the fly the longer it keeps in motion after it is once started.

When heat is applied to either pole of the bulb *negative* rotation takes place. The molecular pressure proceeding

from a hot pole of the bulb will strike the *inner* surface of the sloping vanes. and driving them before it, will cause a rotation which appears *negative* to an observer, although it is really *positive* to the direction of pressure. Fig. 11 sufficiently illustrates this mode of action. The heat is supposed to be applied near the centre, and the molecular pressure, radiating on all sides, presses the vanes chiefly on the inner surfaces. The anomalous results obtained when the radiometers were heated with hot glass shades or hot water are thus accounted for. Polar heating gives *negative*, and equatorial *positive*, rotation, and when both are applied together by immersion in hot water, the direction of motion is governed by the stronger of these two forces.

In my description of Fig. 7 (p. 534) I showed that the glass heated by the ultra-red rays became hot, and acted on the driving surface, generating molecular pressure, and causing the sloping vanes to turn in the positive direction. At the same time the vanes get warm and become themselves sources of molecular pressure. The amount of molecular pressure thus generated depends on the capacity of the material of the vanes to absorb heat. Thin mica will hold very little, thick mica will hold more, and aluminium will hold most. This extra capacity for heat causes more molecular pressure to proceed from the aluminium and thick mica, and generates a proportionate amount of driving power on the surfaces of the vanes, turning them in the positive direction, and supplementing the action of the equatorial ring of hot glass.

The next subject of investigation was the action of radiation on cones, cylinders, and cup-shaped vanes. A pair of

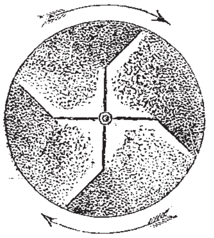

FIG. 10.

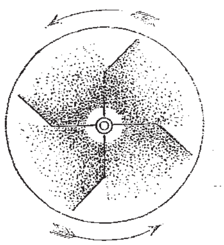

FIG. 11.

thin aluminium disks, cut half across the diameter, were bent into cones and mounted on two arms as a radiometer, the cones facing opposite ways. Several experiments were tried and repeated with cones of different material. The movement which appeared most anomalous was the attraction observed when a candle was allowed to shine on the hollow side of a cone or cup-shaped radiometer, the light being screened off the retreating side. Further experiments, however, showed that the effect of bending the plates, or of making cones of them, is to produce a more favourable presentation to the inner surface of the glass bulb. Radiation falls from the candle on the aluminium; some is reflected and lost, but a portion is absorbed, to be converted into thermometric heat or heat of temperature. Aluminium being a good conductor of heat, and the thickness of metal being insignificant, it becomes equally warm throughout, and a layer of molecular disturbance is formed on each surface of the metal. At a low exhaustion the thickness of this layer is not sufficient to reach from the metal cone to the side of the glass bulb; as the exhaustion increases, this layer extends further from the generating surface, until at a sufficiently high exhaustion the space between the side of the glass bulb and the adjacent portion of the metallic cone is bridged over, and pressure is exerted between the two surfaces. Fig. 12 shows how this pressure will act. The direction of pressure is indicated by dotted lines issuing from the metal cone. The more favourable presentation offered by the cone causes the pressure to be greatest between the glass bulb and the outside of the cone; the pressure from the inside of the cone and from the outside, away from the side of the glass, is dissipated without acting, but the pressure between the glass bulb and the side of the cone nearest to it is active; the cones, therefore, are pressed round in the direction of the arrows, and the motion has the appearance of *attraction*.

Cones being inconvenient in shape, I employed portions of cylinders wherewith to shape the vanes, and I ultimately found that cups were more easily affected by radiation than portions of cylinders, whilst they are more easily fashioned. I found that a four-armed cup-shaped aluminium radiometer, the cups being bright and 10 millims. in diameter, and the radius of the curvature being 6 millims., rotates in the light as well as a flat vaned instrument. I sealed one of these instruments on to the mercury pump. During exhaustion accurate observations were taken of the number of revolutions per minute caused by one or more standard candles 3 inches from the centre of the bulb. I also took observations of pressure, and the exhaustion was carried to a very high point. Fig. 13 shows the curve plotted from these observations, taking the rarefaction of the air in millionths of an atmosphere as abscissæ, and the number of revolutions a minute as ordinates. The curve traced through the dots representing observations illustrates the gradual increase of sensitiveness up to a certain point of rarefaction, and the sudden drop after that point is reached.

To still further investigate the action of dark heat on the vanes, I contrived an apparatus to which I could apply a very intense source of heat always ready in the

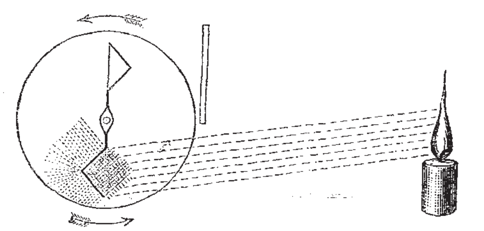

FIG. 12.

same place, the heat not having to pass through glass, and being completely under control as to intensity and time of action. The instrument with which I performed the great number of these experiments is shown in Fig. 14. The cylinder is sealed at the top so as to permit of the highest possible exhaustion. It is drawn off narrow at the end, and a stem is sealed in to hold a needle-point. To the narrow end a fine tube is attached to connect the apparatus to the mercury-pump. Round the needle is placed a ring of fine platinum wire, *a a*, the ends of which are joined to thicker platinum wires passing through the glass. The fly consists of four square vanes of clear mica, *b b*, inclined at an angle of 45° to the horizontal plane and supported on light aluminium arms. Above the vanes is a flat disk of clear mica, *c c*, having a glass cap in its centre, and easily rotating on a needle-point. The vanes and the mica disk are supported independently of each other on separate needle points, which are held in glass rods, *d*, *d*, *d*. A current of electricity from two Grove's cells, turned on or off by a contact key, gives the power of making the wire ring, *a a*, red hot when desired.

The normal or positive movement of the disk is in the opposite direction to that of the vanes; thus, if the positive movement of the vanes is in the direction of the hands of a watch, the positive movement of the disk is in the opposite direction. With the apparatus full of air at the ordinary pressure (bar. = 761 millims.) the direction of rotation, both of the vanes and disk, is *positive* when the platinum wire is ignited. The speed of the vanes is 13·3 revolutions a minute, and that of the disk 1 a minute

At a pressure of 80 millims. the disk does not rotate. The vanes rotate *positively* but slowly.

At 19 millims. no movement whatever takes place. The disk and vanes are as still when the wire is heated as when it is cold.

At 14 millims. the disk remains stationary. The vanes move slowly in the *negative* direction.

At 1 millim. the disk rotates in the *positive* direction slowly, whilst the vanes rotate *negatively* rather fast; the

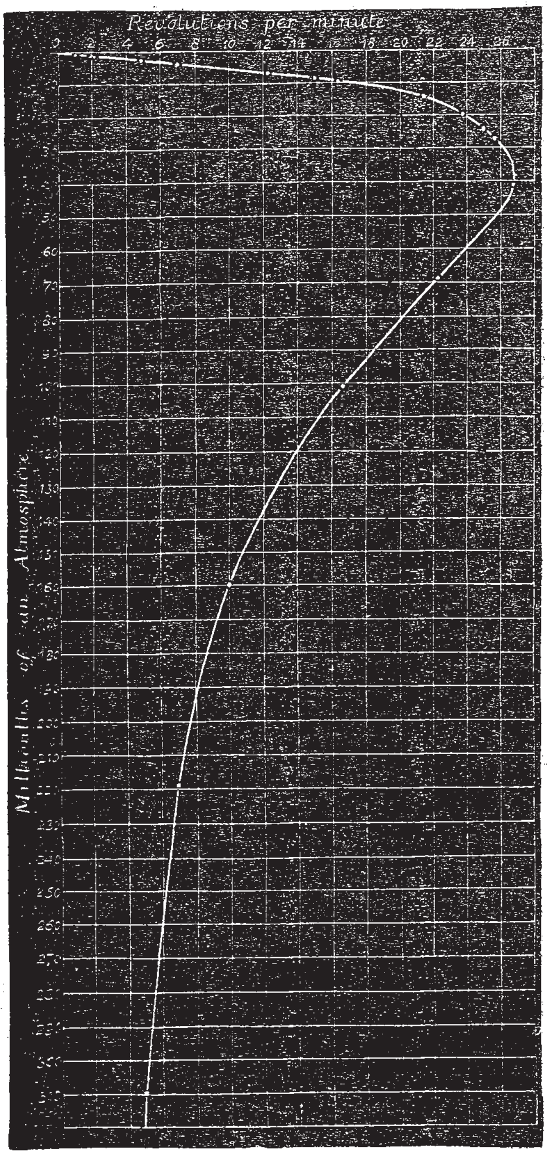

FIG. 13.

disk commences to rotate in the same direction as the vanes at a speed of three revolutions a minute.

(At low exhaustions I speak of millimetres of pressure, but at high exhaustions I prefer to count in millionths of an atmosphere.)

At a pressure of 706 millionths of an atmosphere the direction keeps the same as at 1 millim. in each case, but the disk makes ten revolutions and the vanes forty revolutions a minute.

At 294 millionths, the speed of the disk and vanes is exactly alike, both rotating together in the same direction. Up to this pressure and at some distance beyond, the vanes have been gradually diminishing whilst the disk has been increasing in speed. At a pressure of 141 millionths the disk rotates rapidly, *positively*, but the vanes do not rotate at all. At a little higher exhaustion than the last, viz., at 129 millionths, a great change is observed. The vanes which were still now rotate in the *positive* direction at a speed of 100 revolutions a minute, whilst the disk rotates as before, but with a little diminished velocity. I have previously shown, in a paper to the Royal Society, that the viscosity of air at a rarefaction of 129 millionths of an atmosphere is only a little less than its viscosity at the normal density, and hence it is certain that the vanes at a speed of 100 revolutions a minute exerts a considerable drag upon the disk when it rotates in the opposite direction.

As the rarefaction increases above this point, the speed of both the disk and vanes increases till those of the latter exceed 600 revolutions a minute.

To carry these experiments to a much higher exhaustion it was necessary to modify the apparatus. The complex apparatus I now employed is shown at Fig. 15. Only the upper part of the pump *a b* is shown. It has five fall tubes and is fitted with a small radiometer, *c*, and a McLeod measuring apparatus, *d e*, to enable the degree

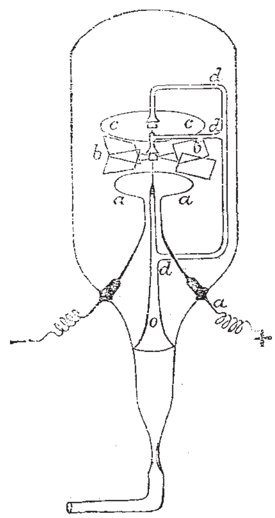

FIG. 14.

of exhaustion in the apparatus to be ascertained. The phosphoric anhydride, for absorbing aqueous vapour, is contained in the horizontal tube *f*. In order as far as possible to prevent the passage of mercury vapour, three long narrow tubes *g g* are introduced between the pump and the apparatus to be exhausted; the one nearest the pump is filled with precipitated sulphur, the centre tube contains metallic copper reduced from its oxide, and the third tube phosphoric anhydride. At *h* is a vacuum-tube containing aluminium wires, and having a capillary bore for examining the spectra of the residual gas. An induction coil and battery are connected with the tube by wires. From the tube *h* two tubes branch off, one of them, *i*, leads to the "viscosity" apparatus contained in the case *k*, and the other, *i*, goes to the apparatus to be exhausted.

The apparatus *s*, containing the rotating disk and vanes, is sealed to the tube *j*. The platinum ring is ignited by the battery *t*. On the top of the ring rests a disk of mica, H, lampblacked on the upper surface; this cuts off direct radiation from the hot ring, and diffuses the heat somewhat over the surface of the black mica. Instead, therefore, of the molecular pressure starting from

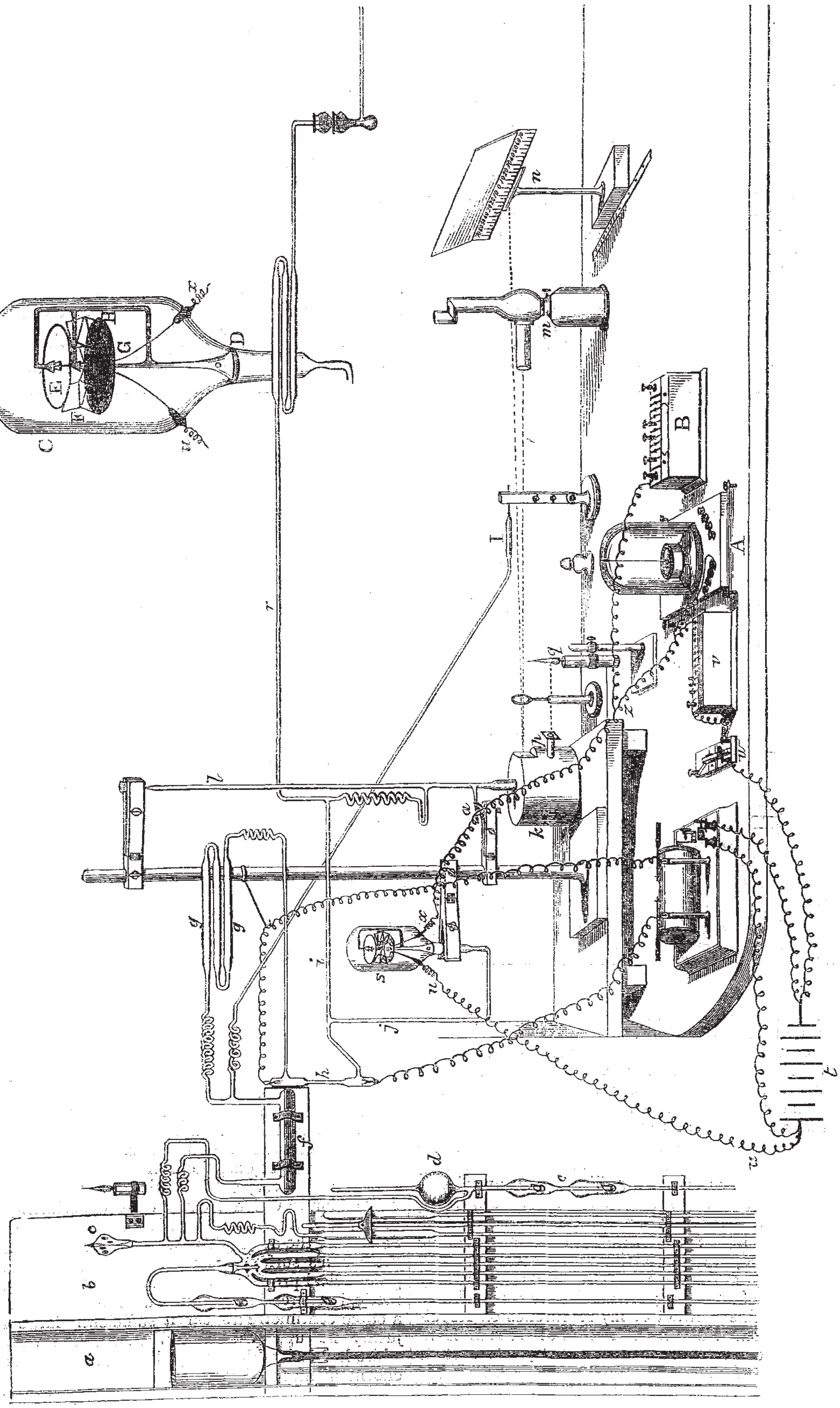

Fig. 15.

the wire, as in previous experiments, the blacked mica now becomes the driving surface.

The whole of this complicated arrangement of apparatus is connected together by actual fusion of the glass tubes one to another; no joint whatever occurs in any part, and a certain point of exhaustion being once attained, I can leave the apparatus to itself with the certainty that no leakage from without can occur.

I take an observation with this apparatus as follows: Arriving at a point when a depression of the contact-key tells me by the behaviour of the rotating disks that a useful observation can be taken, the pressure is first measured in the McLeod apparatus. The viscosity of the gas is then observed, and next the repulsion exerted on the viscosity-plate by the candle. At a very high exhaustion the appearance of the induction in the tube *h* is also noted, together with the spectrum given by it. The strength of the current being first regulated by the resistances *v*, the key, *w*, is pressed down, and the direction and speed of the vanes and disk in *s* are taken by a chronograph recording to tenths of a second. Frequently duplicate or triplicate observations are taken at each pressure, time being allowed to elapse between the observations for the apparatus to become cool.

With this apparatus observations can therefore be taken at each pressure, on the velocity of rotation of the disk and vanes, the viscosity of the residual gas, the repulsion exerted by a standard candle on a black mica plate, and the appearance of an inductive spark through a tube furnished with platinum wire.

In Fig. 16 I have plotted down the observations taken in air-vacua from some of the data I have obtained. These observations are connected together by lines forming curves; in the curve representing the "candle repulsion," I have interpolated a few observations from other experiments to fill up a gap between 59 millionths and 14 millionths, and to give a better idea of the direction the true curve would take. The candle repulsion rises to a maximum somewhere between 59 and 14 millionths of an atmosphere, and then rapidly sinks up to the highest

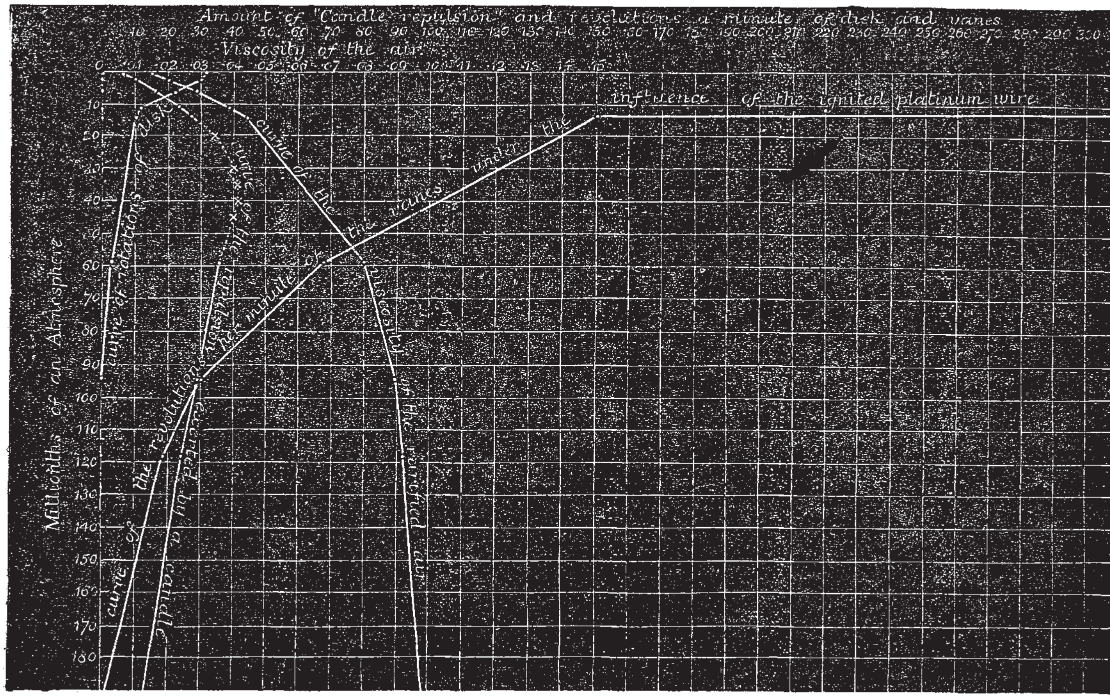

Fig. 16.

exhaustion obtained. Simultaneously the viscosity drops rapidly at the high exhaustions.

When, instead of the feeble intensity of radiation which can penetrate glass from a candle some inches off, I substitute the intense energy of a red-hot platinum wire a few millimetres off, a steady increase of speed from 67 revolutions a minute at 59 millionths, 150 revolutions at 14 millionths, 600 revolutions at 11 millionths, up to over 1,000 revolutions at 6 millionths, and still increasing speeds at 2 millionths and at 0·4 millionth. At an exhaustion, where the repulsion set up by the candle is least, that caused by the hot wire is greatest.

In air, at still higher exhaustions, I could detect no falling off of speed, but in a series of observations with hydrogen I thought there was a diminution of velocity after 1 millionth of an atmosphere had been reached.

In concluding this abstract of my researches on Repulsion resulting from Radiation, I cannot refrain from pointing out how erroneous the ordinary ideas of a "vacuum" are. Formerly an air-pump which would diminish the volume of air in the receiver 1,000 times was said to produce a vacuum. Later a "perfect vacuum" was said to be produced by chemical absorption and by the Sprengel pump, the test being that electricity would not pass, this point being reached, when the air is rarefied 100,000 times. Now Mr. Johnstone Stoney has calculated that the number of molecules in a cubic centimetre of air at the ordinary pressure is probably something like one thousand trillions. When this number is divided by 2,500,000, there are still four hundred billion molecules in every cubic centimetre of gas at the highest exhaustion to which I carried the experiment, illustrated in Fig. 16—a rarefaction which would correspond to the density of the atmosphere about seventy-five miles above the earth's surface, that is, if its density decreases in geometrical progression, as its height increases in arithmetical progression. Four hundred billion molecules in a cubic centimetre appear a sufficiently large number to justify the supposition that when set into vibration by a white-hot wire they may be capable of exerting an enormous mechanical effect.

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